Are Low Surface Brightness Discs Young?

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Received ______________________; accepted ______________________

ABSTRACT

We reconsider the problem of the age of the stellar discs of late-type Low Surface Brightness (LSB) galaxies by making use of a new IMF recently derived from numerical fluid dynamical simulations (Padoan, Nordlund and Jones, 1997). While a Miller-Scalo IMF cannot adequately describe the photometric properties of LSBs, when we apply the new Padoan et al. (1997) IMF to a simple exponential disc model with parameters appropriate to LSBs, we get excellent fits of the colors and color gradients. We then conclude that: a) The star formation history of LSB disc galaxies can be described by an initial burst of a few times 10^7yr followed by a quiescent period with only sporadic star formation; b) LSBs' discs are not young. The age of the LSB disc galaxies for which colors have been measured are all larger than about 10 Gyr.

1. Introduction

Late-type Low Surface Brightness galaxies (LSBs) are considered to be very young stellar systems, because of their rather blue colors (de Blok, van der Hulst & Bothun 1995, McGaugh & Bothun 1996) and very low oxygen abundances (McGaugh, 1994). Based on these observational evidences there have been recently theoretical suggestions that LSBs are formed inside dark matter halos that collapsed very recently, at $z \leq 1$, from density fluctuations of small amplitude (Dalcanton, Spergel, & Summers 1996, Mo, McGaugh, & Bothun 1994).

In this work we study the colors of LSBs from the point of view of synthetic stellar populations (SSP), and show that LSBs could not be as young as claimed in the quoted literature. Recently one of us (PP) has obtained a stellar Initial Mass Function (hereafter P-IMF) starting from high-resolution numerical simulations of the supersonic random motions in the interstellar medium (Nordlund & Padoan, 1997; Padoan, Jones & Nordlund,1997). Here we will plug this P-IMF into the latest version of our synthetic stellar population code which is based on Jimenez & MacDonald (1997) evolutionary tracks and Kurucz atmospheric models (Kurucz 1992). With this we compute synthetic colors and colors gradients for LSBs (section 2) and we show how these can be used to set tight bounds on the ages of their stellar discs (section 3). We also show that the color gradients are well fitted (section 4), and we speculate on the cosmological implications of these results in section 5.

2. Synthetic stellar populations for LSBs

In the following when we will refer to LSBs' we will always mean the sample of late-type disc galaxies observed by de Blok, van der Hulst & Bothun (1995). For each galaxy of their sample the HI surface density, and the surface brightness profiles in several bands are published.

LSBs are found to be rather blue; the color tends to become bluer in the outer regions of their discs. De Blok, van der Hulst & Bothun (1995) noted that it is difficult to understand the colors of LSBs, if their stellar population is old or forming at a declining rate. McGaugh and Bothun (1996) from the analysis of their sample concluded that the stellar populations in LSBs must be very young, because of the very blue colors and of the very low metallicity. In fact an IMF appropriate to the solar neighbourhood, like the one by Miller and Scalo (1979), has a shape very flat for $M \leq 0.1 M_{\odot}$ and this results in too red V-I colors when B-V are properly fitted.

Since the discs of LSBs are rather quiescent when compared with HSB discs, we suppose that their colors are an excellent probe of their stellar IMF. Although this can at most be taken as first approximation, it gives an excellent fit to many observed relations, as we will show. Moreover, it allows us to probe to which extent our P-IMF can provide a realistic interpretation of observed data. At variance with other IMF, in the P-IMF there are no free parameters, and it is based on a model for the structure and dynamics of molecular clouds, that has strong observational support (Padoan, Jones, & Nordlund 1997, Padoan & Nordlund 1997).

The P-IMF is designed to model large scale star formation, and contains a dependence on mean density n, temperature T, and velocity dispersion σ_v of the star forming gas. The mean stellar mass is given by:

$$M_* = 1\mathrm{M}_\odot \left(\frac{\mathrm{T}}{10\,\mathrm{K}}\right)^2 \left(\frac{\mathrm{n}}{10\,\mathrm{cm}^{-3}}\right)^{-1/2} \left(\frac{\sigma_\mathrm{v}}{5\,\mathrm{km/s}}\right)^{-1} \tag{1}$$

As a significant example we apply the P-IMF to a simple exponential disc model, with height-scale equal to 100 pc, length scale equal to 3 Kpc, and total mass equal to $\mathrm{M_D} = 3 \times 10^9 \mathrm{M}_\odot$, a set of parameters chosen to be representative of the LSBs. Our results about colors depend only slightly on these particular values, however.

As a measure of the gas velocity dispersion we use the disc vertical velocity dispersion. We also assume that all stars are formed in a cold gas phase, at T$= 10\,K$.

Note that the same stellar mass would be obtained if the vertical velocity dispersion, instead of the height-scale, were kept constant along the radius, because of the dependence on velocity dispersion and density in equation (1).

Fig. 1 shows the IMF predicted for such a disc at 1kpc and 6kpc from its center. The IMF is more massive than the Miller-Scalo (dashed line), but also less broad. The IMF at 6kpc is also more massive than at 1kpc. We then expect that with these properties the stellar populations which will form will be rather blue, and will become bluer at larger distances from the center, as is observed in LSBs.

To compute the synthetic colors we used the latest version of our synthetic stellar population code (Jimenez et al. 1996). The code uses the library of stellar tracks computed with JMSTAR9 and the set of atmospheric models calculated by Kurucz (Kurucz 1992). A careful treatment of all evolutionary stages has been done following the prescriptions in Jimenez et al. (1995), and Jimenez et al. (1996). Different star formation rates and stellar IMF are incorporated in the code, so a large parameter space can be

investigated.

We find that the star formation in LSBs can be adequately described with an initial burst, followed by a quiescent evolution up to the present time. It has been already remarked (van der Hulst et al., 1993) that LSBs' gas surface densities are too low to allow efficient star formation according to Kennicut criterion (Kennicut 1989). Therefore it is reasonable to argue that significant star formation is limited to an initial burst. The duration of the burst is almost irrelevant to the colors, because of its rather old age, but it cannot be much longer than a few 10^7 yr, in order to be consistent with the low metallicity of the synthetic stellar population, and with the low oxygen abundance of the HII regions observed by McGaugh (1994) in LSBs.

We find that the colors of LSBs are not difficult to reproduce, as long as stars smaller than $1M_\odot$ are not as numerous as in the solar-neighborhood population, which would give a too red V-I color, and as long as a low metallicity is used. Indeed, one can easily see, from the theoretical models by Kurucz (1992), that even a *single* star with low metallicity (Z=0.0002) can reproduce the colors of LSBs. As an example, the colors of a typical galaxy from the sample of de Blok, van der Hulst, & Bothun, namely F568-V1, are: U-B=-0.16, B-V=0.57, B-R=0.91, V-I=0.77 (luminosity weighted); the colors of a Kurucz model with temperature T=5500 K, log(g)=4.5, Z=0.0002 are: U-B=-0.17, B-V=0.56, B-R=0.94, V-I=0.75. This model corresponds to a star of $0.94M_\odot$, having a lifetime of 11 Gyr. Obviously, the reason for such a good match does not lie in the fact that the stellar IMF does not contain any star more massive than $1M_\odot$, as suggested in the past (Romanishin, Strom, & Strom 1983, Schombert et al. 1990), but simply in the fact that $0.94M_\odot$ is the mass at the turn-off for the stellar population of F568-V1 in our model, which gives an age for this galaxy's disc of about 11 Gyr.

3. The age of LSBs

In Fig. 2 we plot the time evolution of the colors for a very low metallicity ($Z = 0.0002$), and in Fig. 3 for a higher metallicity ($Z = 0.0040$).

In order to compare the theoretical prediction with the observed colors, we have used the mean values of the luminosity-weighted colors listed in Table 4 of de Block, van der Hulst, & Bothun (1995). Since the color of a stellar population is affected by age and metallicity, we also plot in Fig. 2 the mean of the observed colors, excluding the three galaxies for which U-B is observed and has a positive value. The error

bars represent the dispersion around the mean. It is clear that the fit is excellent for an age of 12 Gyr, and that an age ≤ 9 Gyr is definitely inconsistent with the data.

In Fig. 3 we plot the mean of the colors for the three galaxies with positive U-B. These redder galaxies are better fitted by a higher metallicity, $Z = 0.0040$, which is one fifth of the solar metallicity, and is one of the highest metallicity estimated by McGaugh (1994) in LSB HII regions. The best fit for the age is 9 Gyr.

The effect of the metallicity on the colors is illustrated in Fig. 4 and 5, where we show the trajectories of the time evolution of our models in color-color diagrams. It is evident that we do not find LSBs younger than 9 Gyr, for any metallicity consistent with the observations. The spread in colors is a result of the spread in metallicity, as is shown by the remarkable agreement between the trajectories and the observations. For instance, in the (B-V,U-B) diagram, where the trajectories are well separated, also the observed points show a similar spread in U-B. On the other hand, in the (B-R,B-V) diagram, where the theoretical trajectories are almost coincident, also the observational points are nicely aligned around the trajectories.

Therefore *the ages of LSBs' discs rule out the possibility that they formed from primordial density fluctuations of low amplitude, collapsed at* $z \leq 1$. Such old ages may seem difficult to reconcile with those of the relatively young stellar populations in normal late-type galaxies, that have U-B and B-V colors comparable to those of LSBs, and B-R and V-I even redder. However, the very blue U-B and B-V colors in LSBs are very well explained by the very low metallicities, rather than by the young stellar ages, and the B-R and V-I colors are explained by the lack of small stars (as the P-IMF predicts), in comparison with a Miller-Scalo IMF.

The diagram (B-V,U-B) shown in Fig. 5 is particularly important, because it can be used to estimate the age of single galaxies, without an independent determination of the metallicity of its stellar population. In fact, in that diagram the time evolution is almost horizontal, along B-V, while the metallicity variations are almost vertical, along U-B. In other words, the degeneracy age-metallicity in the colors is broken in such a digram. We can therefore see that galaxies of different metallicities have all about the same age (11-12 Gyr). The horizontal dispersion of the observational points, along B-V, is approximately 0.1 mag, which is comparable to the observational uncertainty. Therefore, the determination of the age of LSB discs with presently available photometry, and without an independent estimate of the metallicity, has an uncertainty of ± 2.0 Gyr (0.1 mag in B-V).

4. Color gradients

An interesting feature of LSBs is their color gradient: LSBs are bluer in the periphery than near the center of their disc (de Blok, van der Hulst, & Bothun 1995).

Our theoretical models predict a color gradient in agreement with the observations. In fact, the exponential disc model has a volume density that decreases with increasing radius, and equation (1) shows that the typical stellar mass in the IMF grows with decreasing gas density, producing increasingly bluer colors.

We have computed the color gradients per disc length-scale, for a model with an age of 12 Gyr, and metallicity Z=0.0002. In Table 1 we show the results, compared with the observational data, which are obtained from the mean of the values listed by de Blok, van der Hulst, & Bothun (1995), in their Table 3. Again, we have excluded from the mean the three galaxies with U-B>0, since they require a metallicity significantly larger than Z=0.0002. Together with the mean gradients, we give the mean of the errors listed by the above mentioned authors.

The agreement between observational data and theory is striking. Note that the model is just the one that best fits the colors of LSBs, as shown in Fig. 2, rather than being an ad hoc model which fits the color gradients. Therefore *the color gradient of LSBs indicates that the stellar IMF is more massive towards the periphery of the discs than near the center*, as predicted by our P-IMF.

5. Conclusions

In this work we have shown that the P-IMF, applied to a simple exponential disc model, allows an excellent description of the colors and color gradients of LSBs. This allows us to draw a few interesting consequences:

- The Miller-Scalo IMF produces too red V-I colors, and therefore cannot describe the stellar population of LSB galaxies;
- The P-IMF, applied to a simple exponential disc model with an initial burst of star formation, produces excellent fits of the LSBs' colors and color gradients;
- The metallicity of LSB stellar populations ranges from practically zero to about one fifth solar.

- Although most stars in LSBs are formed in an initial burst, a relation between colors and surface brightness is not expected, because the colors are strongly affected also by the metallicity.
- The age of LSBs, inferred from the UBVRI colors, is between 9 and 13 Gyr. These disc populations are therefore about as old as the disc of our Galaxy.
- Since LSBs galaxies are old they cannot be explained as late collapsed objects (low density fluctuations at $z \leq 1$), therefore their origin remains still unexplained.

This work has been supported by the Danish National Research Foundation through its establishment of the Theoretical Astrophysics Center. RJ and VAD thank TAC for the kind hospitality and support.

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Figure Captions

Figure 1: The theoretical IMF at 1 Kpc and 6 Kpc from the center of the disc (continuous lines). The dashed line shows the Miller-Scalo IMF. The theoretical IMF are more massive than the Miller-Scalo one.

Figure 2: The plot shows the time evolution of the colors in a model with metallicity $Z = 0.0002$ and star formation in a initial burst of 5×10^7 yr – the continuous line is U-B, the dotted line is B-V, the dashed-dot line is V-I and the dashed line is B-R. The symbols represent the observed mean values for the sample of LSBs (de Blok et al. 1995) excluding the galaxies with U-B $>$ 0.

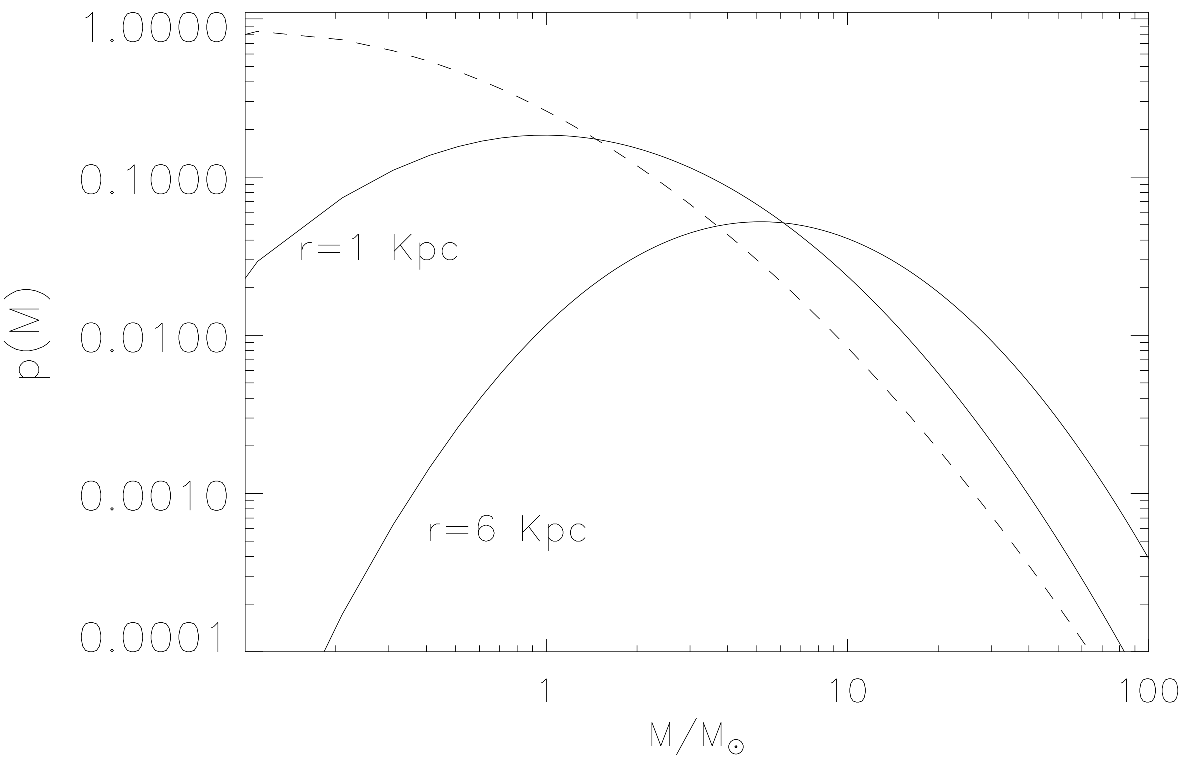
Figure 3: The same as Fig. 2 but for Z=0.0040. In this case the symbols represent only the mean value for the three galaxies in de Blok et al. (1995) sample with U-B $>$ 0.

Figure 4: Trajectories of the time evolution of the models in the (B-R,B-V) diagram. The continuous line is the model with $Z = 0.0002$, and the dashed line the model with $Z = 0.0040$. The diamonds are the observed luminosity weighted colors of LSB discs, from de Block et al. (1995). The trajectories are from 1 Gyr (left) to 14 Gyr (right). The vertical line marks the 9 Gyr age for the lower metallicity. Here the degeneracy is not broken: age and metallicity change in almost the same direction, and in fact the observational points are now nicely aligned with the theoretical trajectories. The vertical and the horizontal lines mark the age of 9 Gyr for the lower metallicity. On the right of the vertical line and above the horizontal one, the models are older than 9 Gyr.

Figure 5: The same for the (B-V, U-B) diagram. All galaxies are clearly older than 9 Gyr. This diagram breaks the degeneracy age-metallicity in the colors.

	Δ (U-B)	Δ (B-V)	Δ (B-R)	Δ (V-I)
de Blok et al.	-0.15 ± 0.14	-0.07 ± 0.12	-0.18 ± 0.08	-0.18 ± 0.17
this work	-0.04	-0.07	-0.14	-0.15

Table 1:



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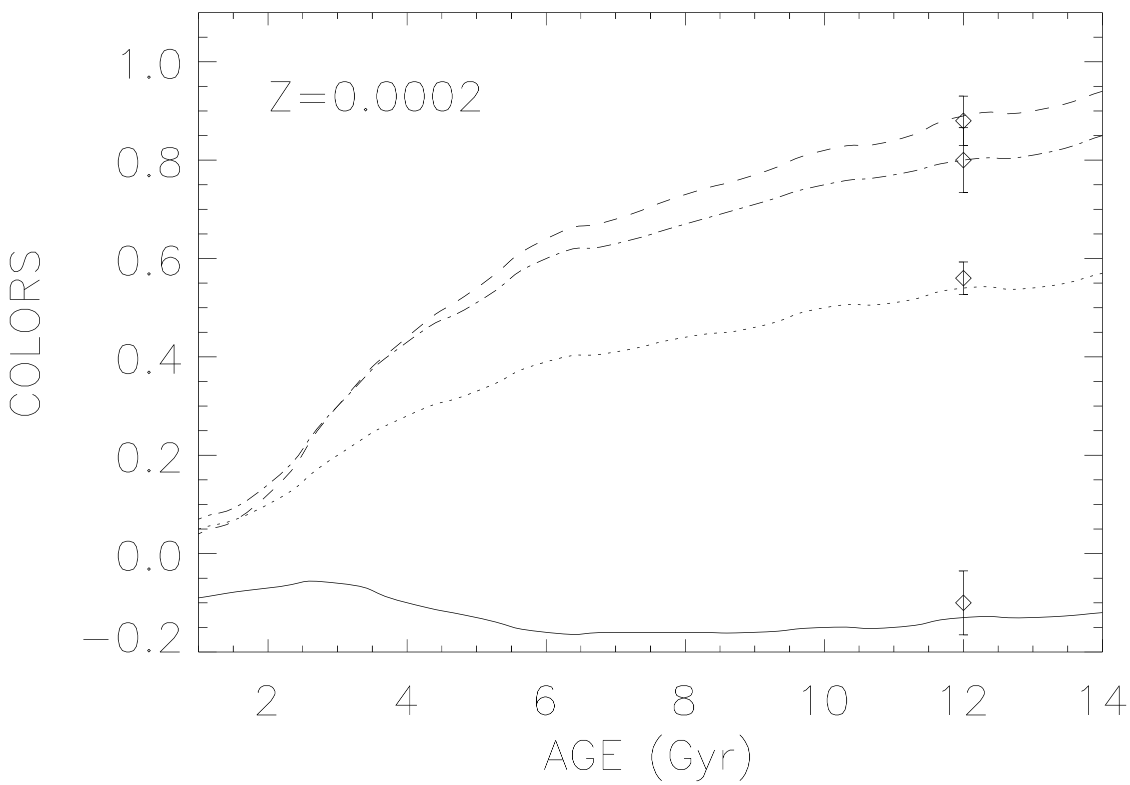
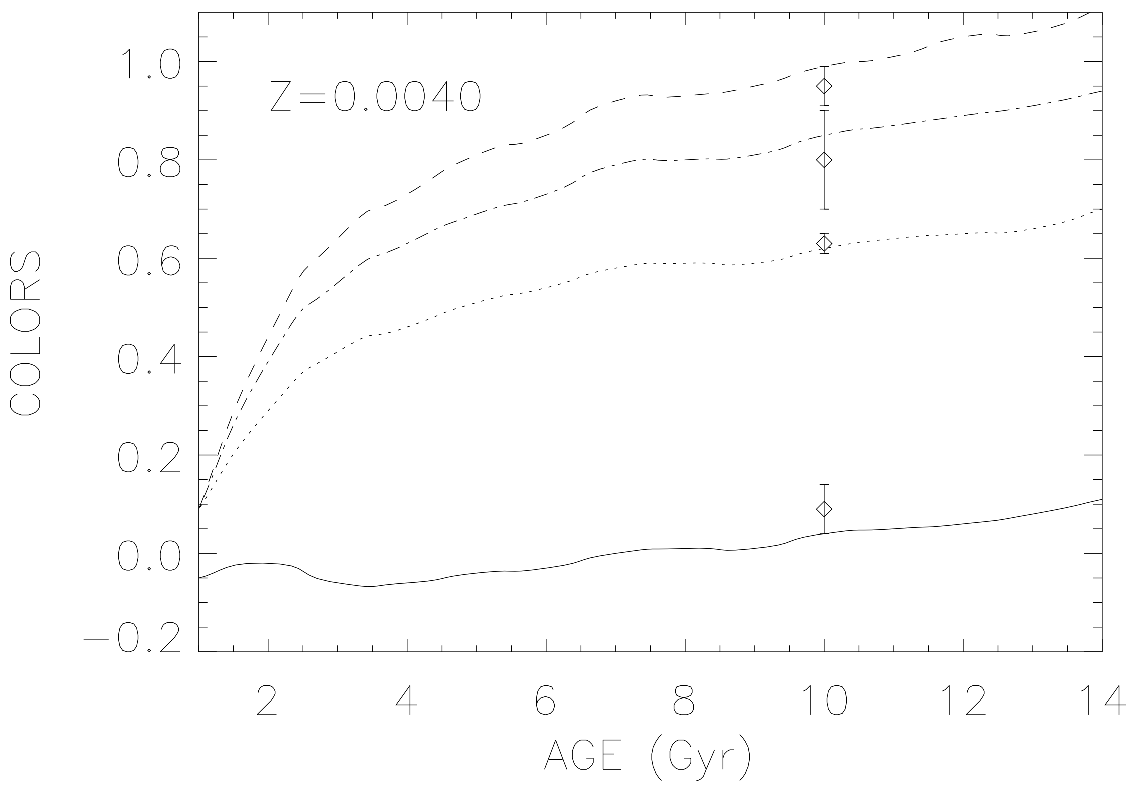


Fig. 2.—



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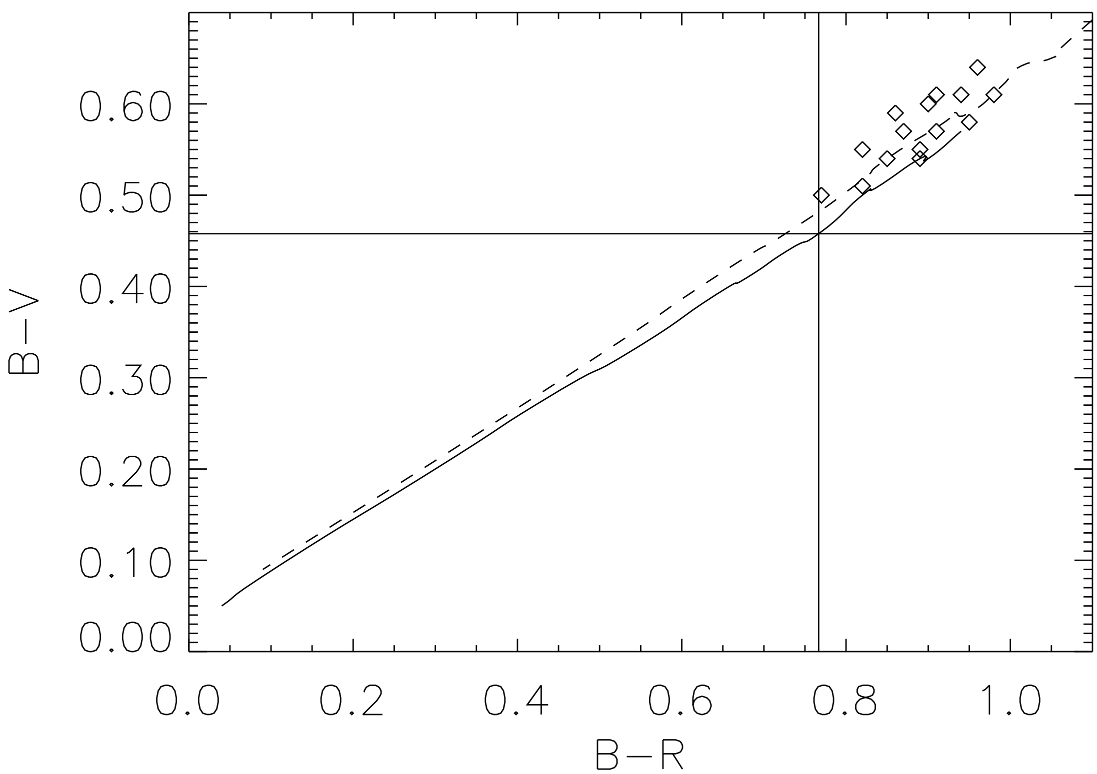
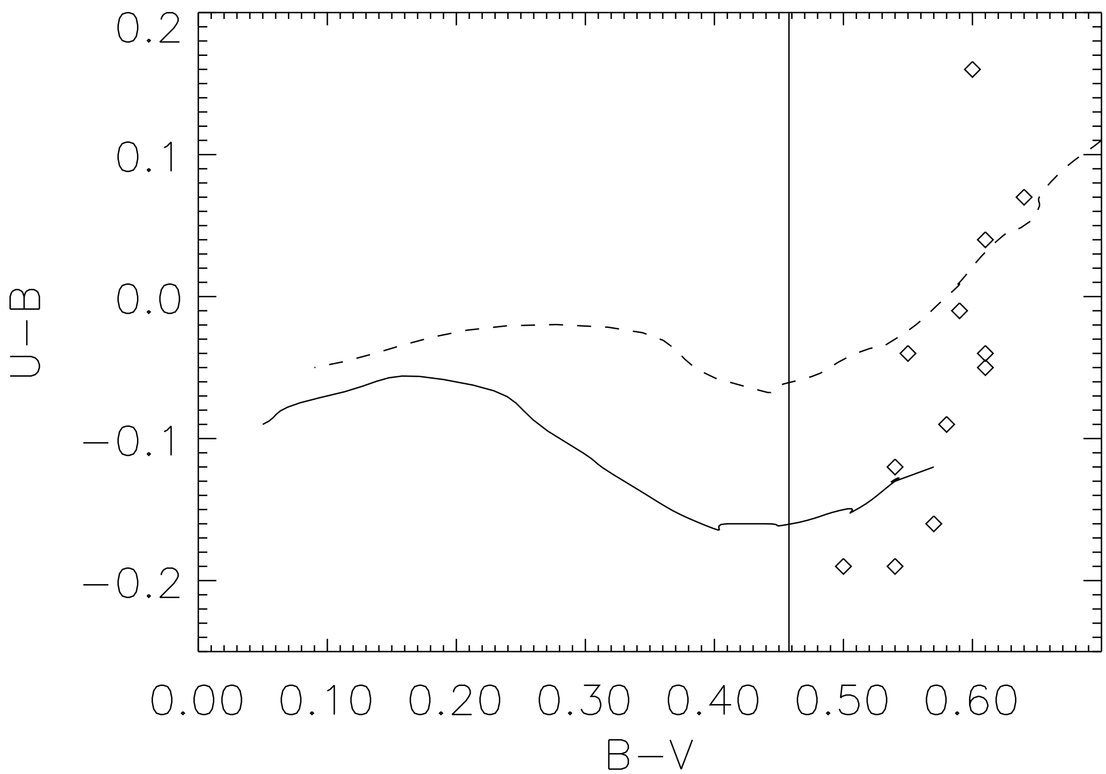


Fig. 4.—



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